

**Title: Electro-magnetically Enhanced Current Interrupter**

**Field of the Invention**

5 [0001] The invention relates to a current interrupter for an electrical circuit, and in particular one which is well-suited for use with a high-current circuit.

**Background**

10 [0002] A typical meltable fuse-type electrical interrupter includes a conductor portion which melts upon reaching a threshold current, the melting being caused by the increase in temperature associated with the current increase and the accompanying  $I^2R$  effect. Once melted, the molten conductor flows, as a result of gravity and/or surface tension, away from the related conductors and the fuse thereby opens the circuit. Devices of this sort are generally described in U.S. Patent Nos. 4,368,452 to Kerr Jr. and 4,622,534 to Bowman.

15 [0003] Such fuse devices, however, are unsuitable for high current use. As currents increase, so too does the fusing temperature and, at very high currents, the fusing material will vapourize once the threshold current is reached, since the material cannot be removed from the vicinity quickly enough and electricity continues to flow through the molten conductor. Arcing results and, as arcing may continue to occur through the medium of the vapourized conductor, arc-extinguishing measures such as the provision for silica sand or a gas must be provided to permit the device to work as intended in high current circuits. The devices therefore often end up being complex, expensive, heavy and of decreased reliability.

25 [0004] Another drawback of the meltable fuse type interrupter is that gravity is relied upon to remove the melted conductor from the circuit to thereby open the circuit. In applications where fuse attitude or gravity may vary (e.g. airborne or space applications), these types of meltable fuses may also be unsuitable. Also, reliance on gravity slows response times. Accordingly, there is a need for improvements in interrupters, particularly for use in high current-carrying circuits and/or variable attitude applications, and it is an object of this invention to provide such a device.

## **Summary of the Invention**

[0005] In one aspect the invention provides at least ...

## **5 Brief Description of the Drawings**

[0006] For a better understanding of the present invention and to show more clearly how it may be carried into effect, reference will now be made by way of example to the accompanying drawings, in which:

10 [0007] Figure 1 and 2 are schematic views of a simple conductor, viewed as lateral and axial cross-sections, respectively;

[0008] Figure 3 is a schematic cross-sectional view of an embodiment of the present invention, shown in the "closed" state;

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[0009] Figure 4 is the device of Figure 3, shown in the "open" state;

[00010] Figures 5 and 6 show alternate embodiments of the device of Figure 3, both in the "open" state;

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[00011] Figure 7 is a side view of a gas turbine engine with a portion broken away to show an electric machine incorporating the present invention therein;

[00012] Figures 8a and 8b are enlarged partial isometric and cross-sectional views,  
25 respectively, of an example electric machine of Figure 7; and

[00013] Figures 9a and 9b show a further alternate embodiment of the device of Figure 3, in the "open" and "reset" positions, respectively.

## **30 Detailed Description of the Preferred Embodiments**

[00014] The present invention makes use of a magnetic force related to current flow through a conductor, which may be used to move a such a conductor when in a molten or liquid state. Referring to Figure 1, when a current  $I$  flows through a conductor  $C$  (in a direction into the page, in this example), magnetic forces  $F_m$  generated as a result of current flow through the conductor act on the conductor in a constrictive and compressive direction. Referring to Figure 2, the net force acting on the conductor results pressure  $P_m$  within conductor  $C$  which tends to want to cause flowing of the conductor in a direction  $m$  generally normal to the direction of  $F_m$ , in this case, an axially outward direction. The pressure  $P_m$  can be derived from Lorenz equations and may be expressed simply as

$$P_m = I^2 * K * \mu / \pi R^2 \quad (\text{Equation 1})$$

where,  $P_m$  is pressure [Pa],  $I$  is current [A],  $K = \mu_0 / 4\pi$  (where  $\mu_0$  is the permeability of free space, or  $1.257\text{e-}6$ ),  $\mu$  is the permeability of the conductor relative to  $\mu_0$  at its melted condition, and  $\pi R^2$  is the cross-sectional area of the conductor [ $\text{m}^2$ ] (where  $R$  is the radius of the conductor [m]).

[00015] **Example 1:** A 0.080 inch (2 mm) diameter conductor with a permeability  $\mu = 1.0$  will develop a magnetic pressure of about 4 psi (27.5 kPa ) at 1000 A.

[00016] **Example 2:** A 0.062 x 0.125 inch (1.5 x 3 mm) lead-silver solder conductor material (melting temperature  $315^\circ \text{C}$ ) connected to adjacent copper conductors (i.e. in a configuration like that shown in Figure 3) can be made to rupture according to the present invention at approximately 800 A.

[00017] The force  $F_m$  and the pressure  $P_m$  is greatest at the core of the conductor, while this force and pressure at the outer periphery is zero. Thus the net effect is a axial pumping effect on a liquid conductor, which tends to squeeze the conductor in a manner roughly analogous to a tube of toothpaste being squeezed around its circumference. At normal current levels, the  $F_m$  forces are not easily measured nor are they influential on the conductor, however, when the conductor is a fluid (e.g. a melted metal) and  $P_m$  is sufficiently high, the magnetic pressure developed as a result can result in motion or

flowing of the fluid which the inventor has found may be used in constructing the present interrupter.

[00018] The inventor has found that material selection and design configuration will permit the designer to methodically employ the current flow and magnetic interaction in the conductor to 'pinch' or 'pump' a molten conductive fluid, such as a melted link element in an electrical interrupter, to thereby open the associated circuit when a certain threshold current is reached, as will be described further below. In this way, the adverse effects associated with vapourization of prior art fuses can be avoided, since the link material is substantially 'pumped' away before its temperature is elevated to a vapourization temperature. When the current flowing through the conductor is high enough to cause the link material to reach the melting temperature, the core of the now molten conductor tends to flow outward, in both axial directions (see Figure 2), resulting in a reduction in the diameter of the conductive path. Referring again to Equation 1, it becomes apparent that the motive force  $F_m$  or pressure  $P_m$  will be inversely proportional to the square of the conductor radius such that, for example, when the conductor radius is diminished by half, the motive pressure increase 4 times, and so on. This results in an ever accelerating flow of the material out of the conduction path. Such an interrupter therefore minimizes the effect of arcing and vapourization simply and by design.

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[00019] Referring to Figure 3, an embodiment of an electrical interrupter 10 according to the present invention is shown. The interrupter 10 includes a meltable (preferably) metal link 12 which adjoins two adjacent conductors 14, for conducting current therebetween, and an insulated sleeve 16 surrounding both the conductors 14 and the link 12. Adjacent the link 12 is at least one, and preferably at least two reservoirs 18. Reservoirs 18 are preferably empty in the initial 'closed' state, and are preferably sized to have the same or larger volume as the volume of link 12 in its melted state, as will be described in more detail below. Reservoirs 18 are preferably closely located to link 12 and in fluid communication therewith, and more preferably communicate with link 12 via openings or connecting passages 20 provided to permit fluid communication for molten link material 12' between link 12 and reservoirs 18. Passages 20 preferably communicate

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with the core or centremost portion of link 12 since, as mentioned above, this is the region of highest pressure  $P_m$ . Passages 20 are also preferably themselves non-conductive so as not to be subjected their own magnetic pressure effect as a result of current conducted therethrough. Conductors 14 are adapted for connection to an electrical circuit (not shown) in any suitable manner. The reservoirs may be empty in their initial state, or may contain a fluid, such as an arc suppressing fluid, cooling oil or other fluid, which is either displaced by the conductor, or pumped into the conductor's original position, or mixed with the conductor, etc.

10 [00020] In the described embodiment, conductors 14 are of preferably generally rectangular cross-section and are made of copper (any suitable cross-section and conductor material may be used). Link 12 is preferably also of generally rectangular cross-section in this embodiment and is preferably made of a eutectic material, and more preferably Indalloy #182 (a trade mark of the Indium Corporation) having a formulation  
15 of 80%Au (Gold) 20% Sn (Tin) and a melting temperature of 280° C. Referring again to Equation 1, Indalloy #182 has a permeability  $\mu$  of 1.0 (whereas conductive materials containing iron or nickel would be greater than 1). Link 12 and conductors 14 are joined by any suitable means. The link material is selected generally based on its melting  
20 temperature corresponding to the selected threshold current, though mechanical properties and oxidation resistance are also desirable to consider. The conductor material is preferably selected, among other things, to remain in its solid state until the threshold current is reached. A eutectic metal material is preferred for its well-controlled melting point and its strong mechanical material properties, however while eutectic materials are preferred, other materials may also be used. It is also possible to design the interrupter  
25 10 to operate based on a pre-selected current, as is presently done with prior art fuses, using power dissipation and heat balance/conduction to the environment to set the temperature at a particular current. Equation 1 will be relevant in selecting the conductor material for link 12.

30 [00021] Reservoirs 18 are preferably two in number and generally cylindrical holes or voids in conductors 14, the volume of these cylinders preferably being approximately

equal to or larger than the calculated volume of link 12 when in its molten state.

Reservoirs 18 are preferably cut or punched into conductors 14 after conductors 14 have been assembled to link 12, though any method of providing them may be used.

5    **[00022]**   In use, in normal operating conditions, the current  $I$  (indicated by the arrows in Figure 3) flowing through the electrical circuit (not shown) passes into interrupter 10 through a first conductor 14, around a first reservoir 18, through link 12, around a second reservoir 18 and then through a second conductor 14 and then to the remainder of the circuit. In the event of a current increase in the circuit, the high current flow generates  
10   increased heat and magnetic forces in the conductors in current path. Referring to Figure 4, when the current  $I$  is high enough to reach a threshold current  $I_{threshold}$ , that is, sufficient to generate just enough heat and temperature rise to melt the link 12, the pressure on the circumference of link 12 resulting from the magnetic forces caused by  $I_{threshold}$  causes the molten metal 12' of link 12 to be forced under the action of this  
15   pressure (see Equation 1) into the spaces provided by reservoirs 18, thereby resulting in a break in the circuit, and thus opening the circuit and preventing current flow. Cooling occurring after the circuit opens results in re-solidification of the link material 12', but in this embodiment the configuration is such that cooling does not allow the fuse to return to a current-conducting state. Note in Figure 4 that the location of reservoirs 18 need not  
20   allow for a gravity feed of link material 12', since gravity is not relied upon in the operation of the interrupter 10.

**[00023]**   As mentioned, the present current interrupter takes advantage of an induced pressure to cause the conductor to flow so as to open the associated circuit.  
25   Consequently, interrupter 10 should be designed taking expected pressures under consideration, as well as temperatures and conductor state, to ensure that sufficient pressure is provided to cause the conductor to move by flowing. The designer will generally consider the heat generated in the conductor at a given current, the melting point of the conductor, and the pressure losses to be overcome in moving the melted  
30   conductor. Pressure considerations which may affect the design include surface tension of the molten conductor, capillary action and viscous losses, as well as losses due to

interrupter geometry. The interrupter design is then provided to ensure that both (a) the conductor is in a flowable state, preferably a liquid state, at temperatures corresponding to a desired threshold, and (b) sufficient magnetic pressure is generated to overcome the calculated pressure losses and thereby cause the conductor to flow accordingly (see

5 Equation 1 and Example 1).

[00024] As mentioned, the magnetic pressure depends in part on the diameter of the conductor. Therefore, it will be understood that as the cross-sectional area of the conductor is reduced (i.e. as conductor material is 'pumped' away), the magnetic pressure

10  $P_m$  increases at a given current, by the square of the ratio of diameters. Therefore, as conductor flow progresses (it will not generally be instantaneous), magnetic pressure increases. Referring again to Example 1, when the volume of fluid is at the half way point in Example 1, the pressure will be 16 psi (100 kPa). The designer may therefore take advantage of this behaviour to ensure that just enough magnetic pressure and

15 flowable conductor is present to initiate cross-section reduction, after which the corresponding pressure increases will 'kick' the rest of the process. Though pressure is dependent on conductor size, material, etc. the magnetic pressure may be as low as 0.1 or .02 psi (0.7 or 1.2 kPa, respectively), or lower.

20 [00025] It will be understood that Figure 4 represents an idealized circumstance in which all of link 12 is melted and flows into reservoirs 18. In practice, however, all that is required in the present invention is that a sufficient amount of link 12 melt and be forced away from adjacent conductor or conductors 14 in an suitable manner to thereby open the interrupter 10 and, thereby, the associated circuit. In practice, the material of

25 conductors 14 may also decay to some extent.

[00026] In another embodiment, depicted in Figure 5, a single reservoir 18' is provided in a different location, and reservoir 18' is larger than the volume of melted link 12. A connecting passage 20 is provided to provide fluid communication for molten link

30 material 12' between link 12 and reservoir 18'. Note that the reservoir 18 need not be on

the 'bottom' side (i.e. closer to the earth) of link 12, since gravity is not a determining factor in the operation of the present invention.

[00027] Referring to Figure 6, in yet another embodiment, reservoir 18 is absent altogether, and link material 12' (not shown) is permitted to be pumped away from the original position of link 12. Again, despite the location of passages 20, the fuse of Figure 6 can be made to operate satisfactorily in any attitude, since gravity is not relied upon by the present invention.

10 [00028] The present system is an active system which overcomes the drawbacks of prior art passive systems, such as fluid viscosity effects and gravity-feed which result in significantly slower response times. The present invention is therefore particularly well-suited for use with relatively high current circuits which do not require fast fusing (i.e. slow blow fuses). When the device is provided such that the threshold current is  
15 sufficiently high, the magnetic pressure at this current will be sufficient to cause the described magnetic phenomenon to 'pump' the melted link as described. At lower currents, the pressure induced will be insufficient to achieve the described result. However, referring again to Equation 1, it will also be understood that what constitutes a 'high' current is dependent on conductor size and composition, among other things.  
20 Therefore, applicability of the device is not limited to traditional notions of 'high current', and with the continual development of nanotechnology, the lower current limit to which this invention is applicable may not yet be known.

[00029] The present invention is particularly well suited, among other things, to  
25 application to protecting an electric machine from damage caused by internal short circuiting. Referring to Figure 7, such an electric machine 119 is shown in a starter-generator application for a gas turbine engine 100.

[00030] Referring to Figure 8a, the current limiting device 10, may be used  
30 beneficially in the secondary or control winding of a permanent magnet alternator of the type described in the applicant's co-pending application serial no. 10/444,952, filed 27



May 2003, the contents of which are incorporated by reference into this disclosure.

Briefly, Figure 8a shows interrupter 10 according to the present invention provided in one or more legs 142 (preferably all legs) of a secondary winding 124. As described fully in the incorporated reference, in use, as rotor 112 rotates around stator 120, magnets 114  
5 induce a current in primary winding 122. The presence and interaction of primary winding 122, secondary winding 124 and bridge 140 extending between adjacent stator teeth 130 also causes an induced current flow in secondary winding 124. Referring to Figure 8b, in use, when the current in secondary winding 124 exceeds a certain threshold, an interrupter element 10 will "open", by link 12 melting, and link material 12' flowing  
10 into reservoirs 18 as described above, and interrupter 10 thereby creating an open-circuit in secondary winding (i.e. no secondary current) and, by reason of the electrical inter-relationship between the primary and secondary circuits, the output current of primary winding 122 will be appropriately controlled. Consequently inductive reactance of the machine is increased, which can be used limit maximum output current to a maximum  
15 synchronous impedance of machine 110. Thus, interrupter 10 can be used in the control of the machine's impedance and in providing machine 110 intrinsic thermal protection against a short-circuit in primary winding 122 when operating in an alternator mode.

[00031] The present invention also presents the designer with various options in  
20 design, unlike the prior art. For example, if for some reason an electrical device including interrupter 10 is operating at normal or low load currents (i.e. there is no electrical fault), but there is a fault which causes overheating in the device (e.g. an interruption of coolant or a very high coolant temperature), the configuration of interrupter 10 may permit the link 12 to melt and escape and thereby open the circuit to  
25 stop operation of the device even though no electrical fault is present. Such operation would of course not have the benefit of the magnetic pressure  $P_m$  caused by an appropriate current level, but nonetheless permits the designer flexibility in providing thermal protection to the device. Conversely, the designer may provide a configuration in which link 12 does not flow to open the circuit unless there is a sufficient current  
30 present to 'pump' away the molten conductor, and in this way the designer may intentionally permit the device to run "hot" as long a threshold current is not exceeded.

In yet another situation, the designer may provide cooling to link 12 to reduce the operating temperature of link 12 even though a current passing through link 12 exceeds an 'uncooled' threshold for link 12, which thereby gives the designer flexibility in selecting when and at what current interrupter 10 will operate to open the circuit.

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[00032] Referring again to Figure 5, another feature of the present interrupter is that it may be provided in a configuration which is automatically intrinsically re-settable. The conductor material may be heated or reheated such that the molten material may flow back to its original location to reconstitute link 12. Gravity feed may be used, or more preferably, a driving current is used to expulse the conductor material from the reservoir 18 and back into its original location as link 12. Since oxidation, etc. would likely be an issue in such re-settable devices, an oxygen-free environment is preferably provided.

[00033] Referring to Figures 9a and 9b, in yet another embodiment, link 12 and reservoir 18 are provided in a re-settable cartridge 22 such that, once interrupter 10 is opened in operation (Figure 9a), cartridge 22 may be repositioned, for example by manual removal and rotation in this example, to reset interrupter 10 by switching the locations of link 12 and reservoir 18, such that their functions and positions are reversed as shown in Figure 9b. Automatic repositioning means (not shown) may alternately be provided.

[00034] Advantageously, with the present invention vapourization of the whole link does not occur as in prior art melting fuse-type interrupters and, therefore, the melt temperature and thus response time can be better predicted in design. In a standard prior art fuse, the overcurrent condition raises the temperature of the fuse material to its fusing or melting temperature. As the temperature increases, the resistance of the material also increases causing an increasing power dissipation in the material ( $I^2R$ ), which causes an increase in temperature and so on. Thus, the prior art fuse is driving itself to ever higher temperatures at an ever accelerating rate until the power dissipation is reduced or eliminated. At some point, a break occurs in the conductive path, which typically causes an arc, particularly in relatively high current situations. This causes local vapourization of

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the conductor which facilitates sustaining the arc, which spreads away from the initial break point vapourizing more material as it progresses, until the voltage needed to sustain a current flow through the now long arc is not available from the external circuit, and the arc becomes quenched. Thus vapourization and arcing are relatively uncontrolled in the prior art, and thus response time and operability is adversely affected. The present invention provides an active pumping effect to minimize the effect of vapourization on arcing, and minimize arcing, which improves (i.e. reduces) responses time.

[00035] Another advantage is that the interrupter according to the present invention may be provided, by design, with an electrical resistance which is lower than possible in the prior art because the initial cross-section of the link 12 (i.e. initial conduction area) has less influence on the threshold current than prior art fuses, because the conduction area is reduced as the link 12 progressively melts.

[00036] The above description is meant to be exemplary only, and one skilled in the art will recognize and changes may be made to the embodiments described without departing from the scope of the invention disclosed. For example, the reservoir(s) need not be empty prior to the fuse activating, but rather the reservoirs may be filled with another material which vacates the reservoirs upon fuse activation, or otherwise is able to admit a sufficient volume of the link 12 to permit interrupter 10 to open the circuit. The function of the reservoir may be served by any means which permits the conductor to be moved away from its initial position to thereby open the circuit. Insulator 16 need not be provided, or may be altered as desired. The link 12 may only partially melt to activate interrupter 10. One or more links 12 may be provided in interrupter 10, of the same or different materials, as desired, arranged in parallel or in serial, as desired. Interrupter 10 need not have a linear shape, nor the rudimentary geometric configuration described, but rather any suitable fuse configuration may be used. Although a meltable solid conductor is discussed through, a suitable conductor which flows in response to magnetic pressure may be used. And although preferred, the threshold current need not be the means by which the conductor is provided in a flowable state, as alternate methods of providing a flowable conductor are available, such as providing separate heating means or providing

a conductor which is otherwise independently in a flowable state. Application of the present principles is certainly not limited to the control of electric machines or use on aircraft. Still other modifications will be apparent to those skilled in the art, in light of a review of this disclosure which do not fall outside the scope of what was invented, and  
5 therefore such modifications are intended to fall within the scope of the appended claims, and their respective equivalents.